MEASUREMENTS OF THE COSMIC-RAY Be/B RATIO AND THE AGE OF COSMIC RAYS

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The ratio Be/B depends on whether the confinement time of cosmic rays in the Galaxy is long or short compared to the radioactive half-life of ^{10}Be. We report observations of this ratio which were obtained with a dE/dx-Cerenkov detector launched into a polar orbit on OGO-6 as part of the Caltech Solar and Galactic Cosmic Ray Experiment. Be/B ratios were determined for various rigidity thresholds up to 15 GV. We find no statistically significant rigidity dependence of the ratio, which is 0.41 ± 0.02 when averaged over all observed cutoffs. When averaged over cutoffs $\geq$ 1.8 GV, the ratio is 0.43 ± 0.03, which can be compared directly to the ratio of 0.42 ± 0.06 calculated by O'Dell, Shapiro, Silberberg, and Tsao assuming ^{10}Be survival. Additional calculations suggest that if the present fragmentation parameters are correct, then the lifetime of cosmic rays in the Galaxy is $< 10^7$ y.

1. Introduction. Knowledge of the lifetime of cosmic rays in the Galaxy is of direct importance to our understanding of the sources and propagation of cosmic rays. The isotope ^{10}Be provides a natural clock, since it decays into ^{10}B with a half-life of 1.5×10^6 y (Yiou and Raisbeck, 1972). O'Dell et al. (1971) calculated that the Be/B ratio should be 0.42 ± 0.06 if there is no decay of ^{10}Be, decreasing to 0.29 ± 0.05 if there is complete decay.

Recently reported observations range from 0.28 to 0.43 (Von Rosenvinge et al., 1969, Buffington et al., 1971, Cartwright et al., 1971, Casse et al., 1971, O'Dell et al., 1971, and Webber et al., 1972), indicating the difficulty of the measurement. Uncertainty in the atmospheric corrections alone could result in a variation of 0.06 in the ratio deduced from balloon-borne experiments (Smith et al., 1973). In addition, the small Be and B fluxes often result in increased statistical uncertainty while charge resolution uncertainties may introduce a systematic bias. The results reported here were obtained with a satellite-borne experiment, thus eliminating the uncertainty in the atmospheric correction. The charge resolution (σ) of our instrument was 0.2 charge units, thus minimizing charge uncertainties. Statistical uncertainty has, however, limited the accuracy in our Be/B ratio to ± 4% for the entire data set.

2. The Instrument. Our data were obtained with a dE/dx-Cerenkov telescope which was part of the Caltech Solar and Galactic Cosmic Ray Experiment (Althouse et al., 1967) aboard the OGO-6 spacecraft. OGO-6 was launched on June 5, 1969 into an 82° polar orbit, with apogee of 1098 km and a perigee of 397 km. The spacecraft was oriented so that the Caltech experiment always

faced radially away from the earth. The low-altitude polar orbit and the radial orientation of the telescope enabled us to sample the entire range of vertical cutoff rigidities from 0 to ~ 15 GV.

A schematic cross section of the telescope is shown in Figure 1. D1' and D2' are Au-Si surface-barrier detectors, 1 mm thick and 2.34 (± 3%) cm in diameter; D3' is the 1 cm-thick fused silica window of a 2-inch photomultiplier tube; and D4' is a plastic scintillator anticoincidence shield. A D2'D3'$\overline{D4}$' coincidence is required for event analysis. The redundant dE/dx measurements supplied by D1' and D2' are used to suppress background caused by nuclear interactions and by detector edge effects. The consistency criteria are carefully optimized to avoid introducing any charge-dependent bias (Brown, 1973).

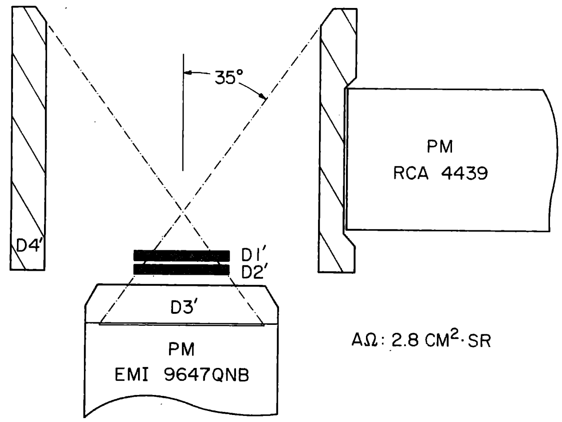

Fig. 1. Cross section view of the dE/dx-Cerenkov telescope.

3. Data. Figure 2 shows data taken at high latitudes, where the geomagnetic cutoff is < 1.8 GV and the low-energy threshold is determined by the Cerenkov threshold of D3' which is ~ 300 MeV/nucleon. The expected positions of each element from lithium to neon are indicated in the figure. Similar curves can be drawn for fractional charges and the events lying in various fractional charge intervals can be summed to form charge histograms such as that shown in Figure 3. Data below the stepped line in Figure 2 are not included in the histograms.

These histograms can be fitted quite well by a sum of Gaussians with $\sigma = 0.2$ charge units. With the resolution thus determined, the events in the histograms can be assigned to the various elements and elemental abundances can be determined.

4. Results. The analyzed nuclei were sorted into five intervals of cutoff rigidity, according to the vertical cutoff rigidity at which each event was detected. Thus, data in each cutoff interval are statistically independent, and the number of events in each interval is directly related to the integral flux of nuclei above an average cutoff rigidity for that interval. In this way, statistically independent ratios of the integral fluxes of Be and B are obtained for each of the five intervals. The observed integral ratios are plotted in Figure 4. The horizontal bars on each point indicate the range of threshold rigidities included in each interval, while the vertical bars indicate the statistical uncertainty (± 1σ) arising from the limited number of analyzed Be and B nuclei. Combining data from all intervals, we obtain

$$\mathrm{Be/B} = 0.413 \pm 0.018.$$

5. Discussion. In order to compare our results with the calculations of O'Dell et al. (1971), we have combined the data from the 4 cutoff intervals above 1.8 GV. The resulting ratio is compared in Table 1 with the ratios

TABLE 1

Comparison of Observed Be/B with Calculations*
(cutoff intervals ≥ 1.8 GV)

Observations:	
Be	370 events
B	860 events
Be/B	0.43 ± 0.03
Calculated Ratio:	
^{10}Be survival	0.42 ± 0.06
^{10}Be decay	0.29 ± 0.05
Difference in Observed and Calculated Ratios:	
^{10}Be survival	0.01 ± 0.07
^{10}Be decay	0.14 ± 0.06

* O'Dell et al. (1971)

predicted by O'Dell et al. (1971) for ^{10}Be survival and ^{10}Be decay. On the basis of this comparison, our results would favor survival of ^{10}Be. It should be noted, however, that the estimated uncertainty in the calculated ratio is larger than the statistical uncertainty in the observed ratio. Any large change in the calculated ratios could significantly affect the above conclusion.

In order to investigate to some degree the sensitivity of the calculated ratios to the assumed parameters, we have calculated the Be/B ratio using the propagation calculation of Meneguzzi et al. (1971), which assumes a steady-state confinement of cosmic rays in the Galaxy, with an escape probability expressed as a leakage mean free path. This model calculation was developed from the "leaky box" model of Gloeckler and Jokipii (1969). Assuming power-law source spectra, the model predicts equilibrium interstellar spectra for each isotope of interest.

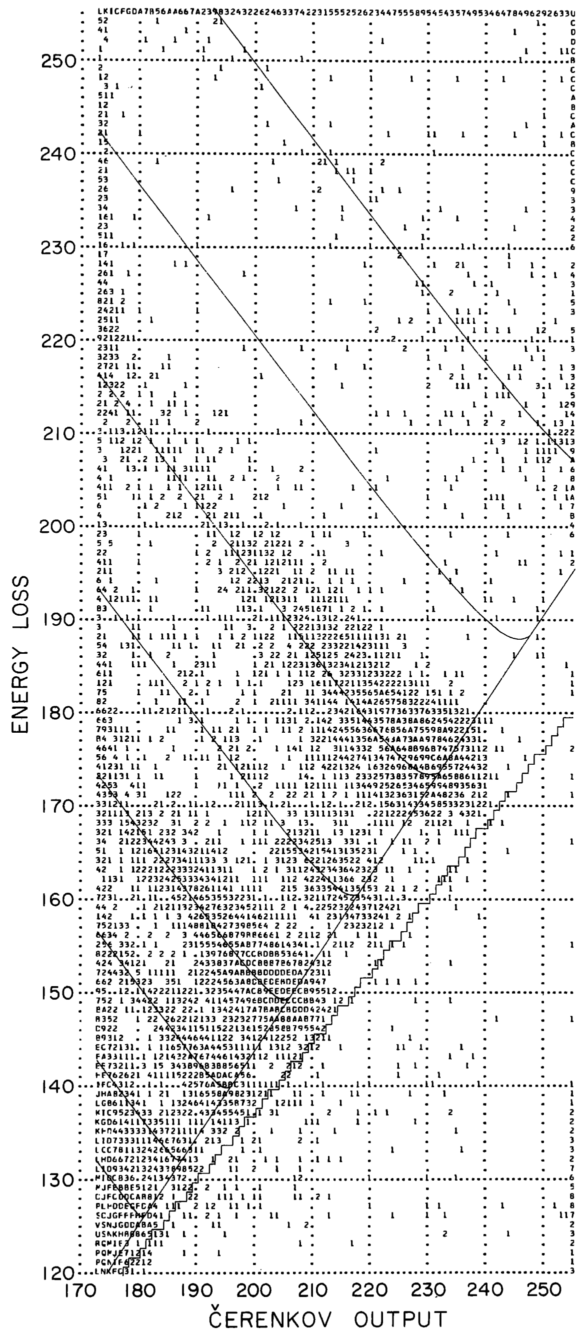

Fig. 2. Pulse-height matrix for cutoffs < 1.8 GV. The curves indicate the expected location of Li through Ne.

We then used these spectra as boundary conditions in numerical solutions of the transport equation for cosmic rays in the solar wind (see review by Jokipii, 1971) using modulation parameters deduced for 1969 from proton, helium, and electron data (Garrard et al., 1973). The result of this solar modulation calculation is a kinetic-energy spectrum at 1 AU for each of the isotopes. The spectra are then integrated to obtain integral rigidity spectra which can then be combined to provide integral rigidity ratios for various elements. The ratios calculated in this way can be compared directly with the observed integral rigidity ratios with no further corrections.

Examples of the calculated ratios for Be/B are included in Figure 4. The curves indicate the predicted ratio as a function of threshold rigidity for interstellar densities of 0.1, 1, and 10 cm^{-3} of H and 10% of He. Since the model assumes a fixed leakage mean free path, a representative value of 8 g cm^{-2} was chosen for this rigidity interval (Brown et al., 1973). A more refined calculation would be required in order to include a rigidity-dependent leakage pathlength.

For purposes of comparison, the ratios in the four highest cutoff intervals were combined into a single ratio for > 1.8 GV. The lowest rigidity interval corresponds to cutoffs less than 1.8 GV for which the incident particle threshold is determined by the Cerenkov threshold of ~ 300 MeV/nucleon. Comparison of these two ratios with the calculated ratios in Figure 4 is summarized in Table 2. The calculated life time τ_e is related to the H and He density n_H and n_{He}, the leakage pathlength Λ_e, the particle velocity βc, and the masses M_H and M_{He} according to

$$\tau_e = \Lambda_e/\beta c(n_H M_H + n_{He} M_{He})$$

(Meneguzzi et al., 1971). Based on the lower rigidity ratio, the leakage lifetime is $10^6 < \tau_e < 10^7$ y, assuming only 1σ statistical uncertainty in the data and no calculational uncertainty. The higher rigidity ratio yields $\tau_e < 4 \times 10^6$ y. Both are consistent with substantial survival of ^{10}Be.

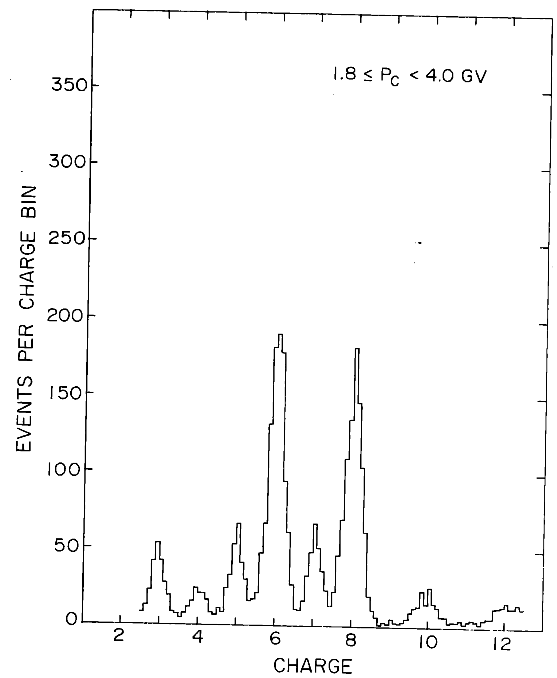

Fig. 3. Charge histogram for data taken in the 1.8 to 4 GV cutoff interval.

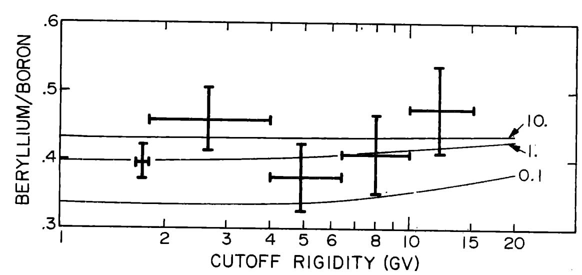

Fig. 4. Observed integral rigidity ratios of Be/B as a function of threshold rigidity. The curves indicate calculated ratios at 1 AU for interstellar H densities of 0.1, 1, and 10 cm^{-3}.

TABLE 2

Estimated Leakage Lifetime

	Cutoff Interval < 1.8 GV	Cutoff Interval > 1.8 GV
Observed Ratio	0.396 ± 0.025	0.43 ± 0.03
Calculated H density*		
lower limit	0.4 cm^{-3}	1 cm^{-3}
nominal	0.9	10
upper limit	4	> 10
Calculated lifetime*		
lower limit	10^6 y	$< 4 \times 10^5$ y
nominal	4×10^6	4×10^5
upper limit	10^7	4×10^6

* Assumes only 1σ statistical uncertainties.

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